Titanium Wire Arc Additive Manufacturing Inert Enclosure and Material Handling Safety Considerations[1]

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Abstract

Wire arc additive manufacturing (WAAM) via metal inert gas (MIG)/gas metal arc welding (GMAW) is a viable option for fabrication of large-scale titanium parts; however, it introduces new safety hazards associated with both the material and the additional system hardware required for the process. Localized gas shielding of the weld arc via standard MIG/GMAW torch is inadequate for titanium due to its affinity for oxygen; thereby requiring the use of an inert enclosure to protect the weld from entraining oxygen. The use of the inert enclosure presents potential safety hazards such as operator asphyxiation and brings up discussion of confined space considerations. In addition, the titanium welding process creates pyrophoric titanium soot residue around the deposit, which can undergo deflagration during part cleaning and part removal. This paper provides an overview of the titanium WAAM process along with safety considerations for the design and operation of the inert enclosure as well as functional solutions for the safe handling of the titanium soot by-product.

Introduction

Titanium is a unique metal that possesses a desirable combination of mechanical, chemical, and physical properties, such as excellent strength-to-weight ratio, corrosion resistance, hardness, and even biocompatibility [1]. Industrial production of titanium began in 1948 [2, 3], and grew into a $24.7-billion USD industry worldwide by 2021 [4]. Aerospace and defense industries take advantage of titanium's excellent strength-to-weight ratio because it is as strong as steel but 45% lighter and is twice as strong as aluminum and only 1.6-times denser [5]. Naval industries, chemical processing facilities, and desalination plants utilize titanium for its corrosion and chemical resistant characteristics, making it ideal for handling ocean water and chemical surfactants [4]. Titanium is even used in surgical implants due to its high biocompatibility and hardness [6].

Traditionally various casting methods have been explored and utilized to produce titanium parts, including rammed graphite and investment casting techniques [7, 8]. These manufacturing techniques, although common, have associated difficulties and limitations, such as requiring specially designed, non-reusable molds to be manufactured for each cast piece [7]. Mold production is difficult to automate, relying on time consuming and labor-intensive manual fabrication [7].

Additive manufacturing offers an alluring alternative to the casting process, boasting the ability to manufacture titanium parts without the additional time, labor, and material costs associated with

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producing casting molds [9, 10, 11, 12, 13, 14]. Several additive methods have been tested and employed by industry. These methods can be roughly categorized into powder- and wire-based methodologies. Powder-based additive manufacturing technologies like binder jetting, laser-powder bed fusion, and electron beam powder bed fusion offer a high level of dimensional accuracy due to the small size of the feed material and the fine control over the powder adherence or powder melting methods utilized in the building process [11, 12, 13]. However, due to the small size of the feed material, rapid production of large-scale parts is difficult for these technologies. Wire-based additive manufacturing methods do not offer the same level of dimensional accuracy but are capable of manufacturing near-net shape part geometries more quickly, making them attractive for the production of larger parts [9, 10, 11, 14, 15]. Investigation of wire-based titanium additive manufacturing processes are being explored, like wire arc additive manufacturing (WAAM), which utilizes standard welding hardware.

Production of titanium parts presents safety hazards due to the reactivity of the material. Titanium powder or soot can be produced as a by-product during manufacturing steps [2]. Titanium powder is a dangerous chemical that exhibits an exothermic, pyrophoric reaction when exposed to oxygen, leading to potential fire and explosion hazards [2,16,17]. Over the past 50 years, there have been six major titanium production accidents in the U.S.; resulting in four deaths, two severe injuries, and over $1 million USD in damages [2]. As such, extreme caution must be utilized during titanium part production along with considerations to minimize the risks it incurs. This paper provides an overview of the titanium WAAM process along with safety considerations for the design and operation of the inert enclosure as well as functional solutions for the safe handling of the titanium soot by-product.

Titanium Wire Arc Additive Manufacturing Overview

Wire Arc Additive Manufacturing, Inert Enclosure Usage, & Titanium Soot By-Product

MIG-WAAM is a well-established process that uses MIG hardware mounted to a robot arm or gantry system to melt and fuse metal wire into weld beads on a metal substrate. These weld beads are fused and layered, one on top of another, to create a 3D object [9, 10], as seen in Figure 1. For this process, inert gas, such as argon or helium, is fed through the nozzle to allow for the creation of an inert environment around the arc that prevents oxidation of the weld bead during metal transfer. Providing shielding locally around the arc, “local shielding”, is adequate for most materials such as mild steels, stainless steels, and many others because the weld temperature drops below the material specific oxygen entrainment temperature quickly enough that the weld quality is acceptable.

Titanium, on the other hand, has a critical temperature for oxygen entrainment of 400-520°C, over which the titanium will strip oxygen form the surrounding environment and entrain it in the weld, leading to severe embrittlement of the part [18]. As the MIG torch moves to continue depositing titanium along the tool path, the freshly deposited, hot trailing weld bead is still above the oxygen entrainment temperature threshold but is no longer within the local shielding range of the torch. As such, an inert environment is needed around the entire weld and part throughout the manufacturing process. In addition, it is important to note that titanium soot is created as a by-product of the welding process and due to the use of the inert enclosure the pyrophoric soot is deposited in a reactive state. As such, a soot collection unit is utilized to help collect and contain the soot; however, some soot is still left on the part. Due to this, caution should be exercised while cleaning the residual titanium soot residue.

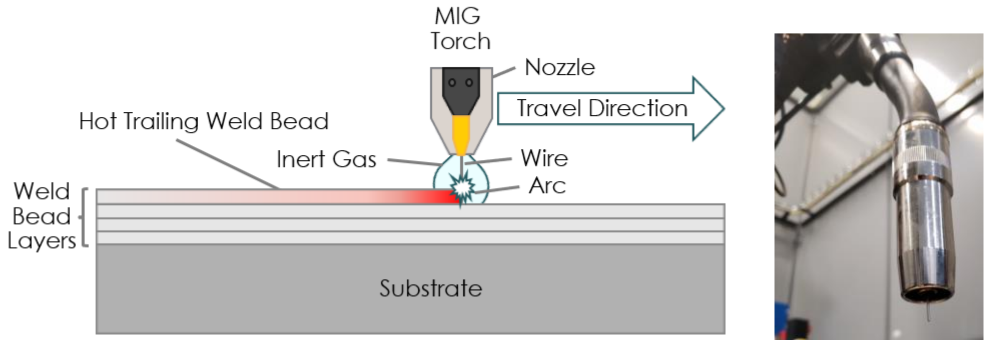

Figure 1: (Left) Wire Arc Additive Manufacturing (WAAM) Process Schematic, (Right) Standard Metal Inert Gas (MIG) Torch

System Operation Steps and Hazards

General cell operation includes steps for substrate mounting and setup, welding, changing of weld tips and nozzles, and cleaning and part removal. These steps present hazards including electrical hazards, arc flash hazards, pressures system hazards, mechanical collision hazards, and fume inhalation hazards. Utilization of the inert enclosure adds steps like argon purging and the reintroduction of oxygen to the enclosure. It also alters existing steps like substrate mounting and setup, which now must be done inside the enclosure, and the changing of weld tips and nozzles, which now must be done via glove access. These changes add hazards such as asphyxiation due to argon gas and working in the confined space of the enclosure. Similarly, working with the pyrophoric titanium soot and the soot collector unit require additional operational, cleaning, and material handling steps and introduce fire and explosion hazards. Table 1 presents the system operation steps for the titanium workflow along with associated hazards and hazard related system components.

Table 1:Titanium WAAM System Operation and Hazard Breakdown

STEP #	PROCEDURE	ASSOCIATED HAZARD	HAZARD CAUSE
1	Mount and setup substrate inside inert enclosure	Confined space hazard	Enclosure specific hazard
2	Purge oxygen from inert enclosure using argon gas	Asphyxiation hazard	Enclosure specific hazard
3	Turn on soot collection unit	Fire and combustion hazard	Titanium specific hazard
4	Weld and manufacture part	Heat hazard	General operation hazard
5	Tip and nozzle change via glovebox access	Asphyxiation hazard	Enclosure specific hazard
6	Part cooling	Heat hazard	General operation hazard
7	Stage-one part cleaning	Asphyxiation hazard, Fire and combustion hazard	Enclosure specific hazard, Titanium specific hazard
8	Removal of argon from enclosure & turning off soot collection unit	Asphyxiation hazard, Fire and combustion hazard	Enclosure specific hazard, Titanium specific hazard
9	Stage-two part cleaning	Asphyxiation hazard, Fire and combustion hazard	Enclosure specific hazard, Titanium specific hazard
10	Part removal	Confined space hazard	Enclosure specific hazard

System Hardware

The Lincoln Electric WAAM cell was utilized for this work. The cell utilizes an ABB IRB 4600 robot arm, controlled by an ABB IRC5 unit. The welding system utilizes a Lincoln Electric Power Wave R450 welder with Power Wave STT Module, an AutoDrive 4R220 wire feeder and an Abicor Binzel WH 500 MIG welding torch.

The custom inert enclosure consists of three key components: the hard-side base structure, the flexible tent, and the cuff connection to the robot arm, as seen in Figure 2. The hard-side base provides structure to the enclosure, has a front and side door, and allows glove access while the system is filled with argon gas. The flexible tent allows for the arm to move freely inside the enclosure. The cuff connection is the interface between the flexible tent and the robot arm and has an internal bearing that allows for play between the robot linkage and the tent during operation.

The system utilizes an LC Technology Solution Inc.SR-225 dry closed-loop soot removal/collection unit. This unit removes soot particulate from the enclosure by circulating titanium soot enriched argon gas from the inert enclosure through a dry filter system before returning clean argon gas back to the enclosure.

Internal to the enclosure there are implements to aid in the processing and safe use of the system. An Abicor Binzel TCS-CC torch cleaning station is a three-stage cleaning station which cuts the wire to the proper stick-out, reams the built-up spatter out of the torch, and applies lubricant inside of the torch to reduce future spatter build-up. The torch clean station is used to minimize system downtime caused by the buildup of spatter and to prepare a fresh wire stick-out for clean weld starts. The glove access allows for use of tools and hardware for interfacing with the torch during the build, allowing for the replacement of consumable hardware such as the welding tips. The IR camera is used to monitor the temperature of the part throughout the build and is implemented as a control for regulation of the bead-by-bead and layer-by-layer inter-pass temperature of the part. Several oxygen (O_2) sensors are utilized as safety features, to monitor air quality in and around the system.

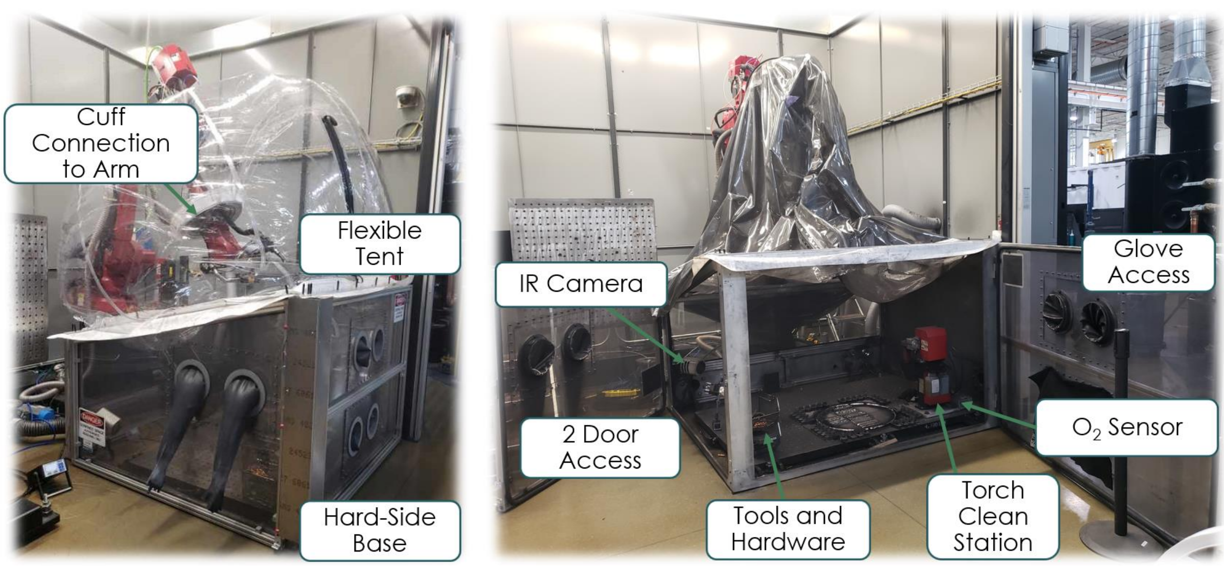

Figure 2:Inert Enclosure Overview

Safety Hazards and Hazard Mitigation

Asphyxiation

This system utilizes argon gas to purge oxygen from the inert enclosure. Throughout the purging process and during normal operation, argon gas is expelled from the enclosure and into the general welding cell area. Argon gas is a colorless, odorless gas that is denser than oxygen [19]; as such, it settles at to areas of lower elevation, displacing oxygen from those areas. This poses a suffocation risk, which has here been addressed by utilizing several oxygen sensors throughout the system as well as the employment of active ventilation for the cell during system use. This system utilizes four oxygen sensors. The first is in the enclosure as seen in Figure 2. This sensor monitors the percentage of oxygen inside the enclosure and is used as a check for internal oxygen conditions prior to opening or entering the enclosure. A second sensor is located outside of the enclosure to provide feedback on air quality safety in the general welding cell area around the inert enclosure. Due to argon being denser than oxygen, these first two oxygen sensors are placed near the ground to monitor the highest concentrations of argon and the lowest concentrations of oxygen. An additional sensor is worn by the operator as an added layer of protection. All three of these oxygen sensors are set to alarm when the oxygen level decreases below 19.5% O_2, below which is considered oxygen deficient air quality [20].

Confined Space

Confined spaces are determined based on three major factors: spaces large enough for bodily entry, spaces having limited means of entry and egress, and spaces not designed for permanent human occupancy. In the cases of large AM systems, like the wire arc cell, the general cell area typically is large enough for full bodily entry but is lacking in design for permanent human occupancy. As such, confined space categorization was largely based on the means of entry and egress. For typical large-scale AM systems, the doors for entry are large or standard size meaning that there is no limited means of entry/egress, thus they are generally not classified as a confined space. However, for secondary or smaller enclosures used within AM systems, entry and egress doors can be significantly smaller than traditional doors. The requirement for door height and width is not a fixed number, but 5.5ft x 2ft is used within OSHA letters of interpretation(s) [21, 22]. The size constraints can be left to the judgement of the individual classifying the space as there are no hard-set numbers, just letters of interpretation. In the case of the inert enclosure, due to the height of the door opening, the space was determined to be a confined space. Once a space is determined to be a confined space, hazard analysis is performed to determine space entry requirements. In the case of ORNL, a space can be classified as a non-permit required entry if all hazards can be mitigated prior to entry thus minimizing the risk to the entrants.

Personal Protective Equipment (PPE)

The welding process creates fine titanium soot by-product during deposition. The titanium soot exhibits an exothermic, pyrophoric reaction with oxygen and is generally classified as a flammable and combustible/explosive substance [2, 16, 17, 23]. As such, during operation of the system personal protective equipment (PPE) is required. Two sets of PPE have been selected depending on the level of interaction when handling the titanium soot, see Figure 3. Secondary exposure PPE is used when the enclosure is closed and in operation. This leverages the additional layer of protection provided by the structure of the inert enclosure between the titanium soot and the operator during glove box access. Primary exposure PPE is utilized when the directly interacting with the titanium soot; this PPE more extensive due to the closeness of handling the potentially hazardous material. Prior to determining the titanium soot particle size, a full-face respirator is used as part of the primary exposure PPE to avoid soot particles inhalation.

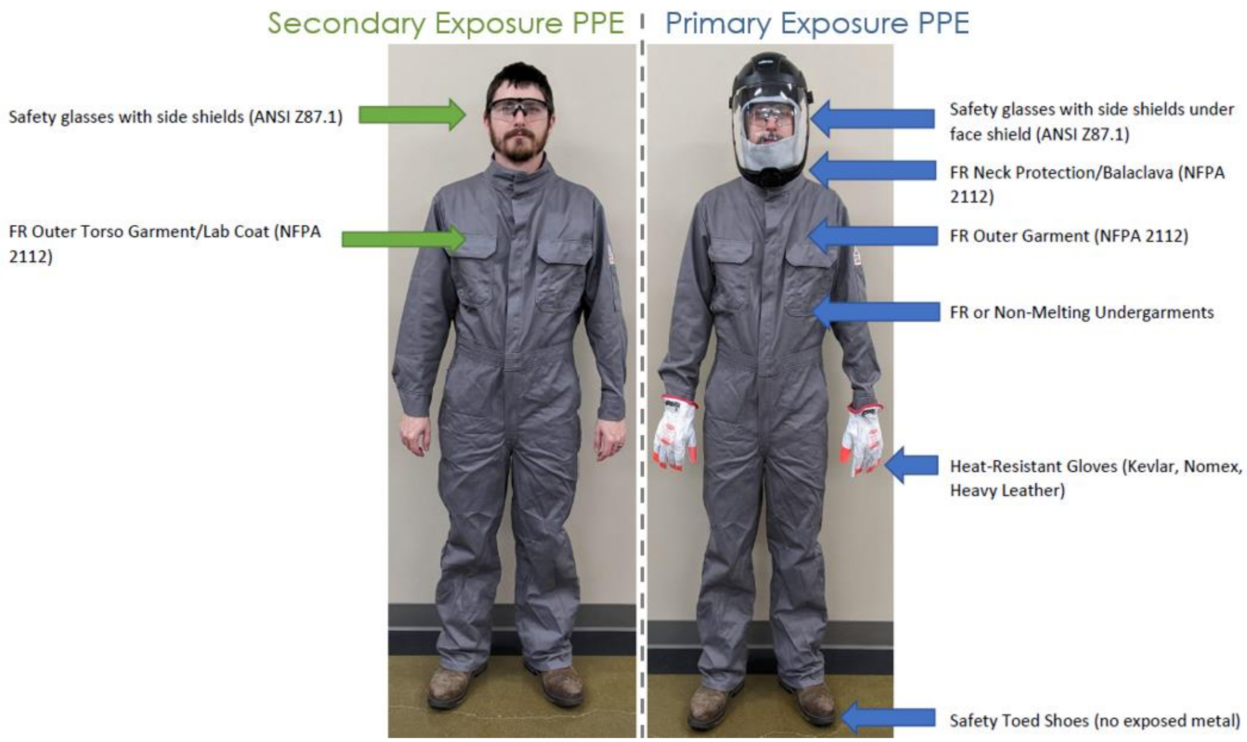

Figure 3: Primary and Secondary Exposure Personal Protective Equipment (PPE) for Handling Titanium Soot

Combustible Soot Particulate

Titanium soot/powder deflagration, see Figure 4, is not a new phenomenon [16], and takes very little energy input to ignite [17]. Soot can be tested for combustion/deflagration risk assessment. These tests assess soot/powder characteristics such as particle size, minimum ignition energy, minimum explosible concentration, minimum ignition temperature, and deflagration index [2, 16, 17, 24]. Smaller particulate size trends with lower minimum energy input, lower minimum ignition temperature, and minimum explosible concentration [2, 16, 17]. The challenge is that unreacted soot must be collected to fulfill the minimum powder volume requirements for these tests. During the primary testing, extreme caution should be utilized.

Figure 4: (Left) MIG Titanium Deposits with Soot By-Product, (Right) Titanium Soot Deflagration/Combustion

The fire triangle and explosion pentagon, seen in Figure 5, show the constituent components of the respective reactions. The use of the fire and explosion polygons allows for the identification of limiting factors for these reactions. Without one side of either polygon, the corresponding reaction cannot take place [25]. Limiting factors can be leveraged through the operation and cleaning process to reduce operational hazards. As such, a two-part cleaning process was applied. After the part was printed and cooled, but while the enclosure was still filled with argon, stage-one cleaning was performed using secondary exposure PPE and a non-sparking brass bristle brush which is handled via glove box access. During this stage the limited oxygen inside the enclosure reduces fire and explosion hazards, allowing for the removal of the unreacted titanium soot from the part. This titanium soot is removed from the part and stored in the soot collection unit. Stage-two cleaning is performed with the system open and the part exposed to atmosphere. This step utilized primary exposure PPE while the part is re-brushed with the brass bristle brush then subsequently cleaned with a grounded combustible soot vacuum. Post-cleaning, the part is safe to be handled with gloves, eye protection, and safety toed shoes.

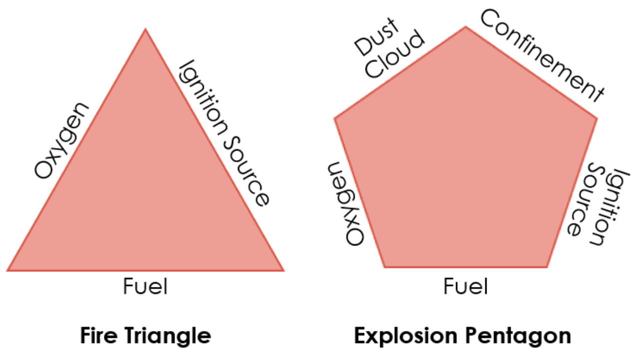

Figure 5: Fire and Explosion Polygons

Conclusions

Wire arc additive manufacturing is a notable addition to titanium manufacturing techniques but presents the need for additional safety considerations. As such, it is pertinent to address these issues through proper use of engineering and administrative controls and personal protective safety measures.

The key hazards addressed here are:

- the risk of asphyxiation due to use of argon gas
- safe egress from and safe operation within the inert enclosure via confined space considerations
- the handling of the titanium soot

Usage of several oxygen monitors internal and external to the enclosure as well as personal oxygen sensor with alarms has proven adequate. Design considerations of the inert enclosure for the ease of egress and rescue should be considered early in the system design process and should be routinely checked to ensure operator safety when working in or around the enclosure. Working around the flammable and explosive titanium soot, a by-product of the MIG welding process, is well handled with the use of a soot collection unit, as well as a two-part cleaning process. The titanium soot should be tested for particle size and flammability and explosion risk via a suitable testing facility.

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